Scalar and fermion on-shell amplitudes in generalized Higgs effective field theory

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Based on **1904.07618** (PRD)
and **2102.08519**
in collabolation with
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HPNP2021, 25 March 2021

Big questions

- SM cannot explain
  - Why EWSB scale ~ O(100 GeV)
  - What dark matter is

⋮

- Physics beyond SM is needed.

Searches for BSM signals

- Direct searches
- Indirect searches

How to organize BSM signals ?

Can we be systematic ?

Higgs EFT

- BSM effects in the SM processes can be described by

$$\mathcal{L}_{\mathrm{HEFT}} = \frac{1}{2}(\partial_\mu h)(\partial^\mu h) + i\psi^\dagger \bar{\sigma}^\mu \partial_\mu \psi \\ + \frac{v^2}{4} F(h)\, \mathrm{Tr}[\partial_\mu U^\dagger \partial^\mu U] - V(h) \\ + M(h)\, \psi_L^\dagger U \psi_R + h.c.$$

Feruglio (1993), ++

- F, V, M parameterize BSM contributions.

Beyond HEFT ?

- We **cannot** compute production/decay rate of BSM particles in HEFT framework.

- HEFT cannot be applied to direct searches.

How can we extend HEFT to include BSM particles?

Talk plan

- Adding spin-0

1904.07618 (PRD)

- Adding spin-1/2

2102.08519

Scalar sector of Higgs EFT

- Scalar sector of HEFT

$$\mathcal{L}_{\rm HEFT} = \frac{1}{2}(\partial_\mu h)(\partial^\mu h) + \frac{v^2}{4}F(h)\,{\rm Tr}[\partial_\mu U^\dagger \partial^\mu U] - V(h)$$

125GeV higgs

NGBs (π^1, π^2, π^3)

Scalar sector of Higgs EFT

- Scalar sector of HEFT

$$\mathcal{L}_{\rm HEFT} = \frac{1}{2}(\partial_\mu h)(\partial^\mu h) + \frac{v^2}{4} F(h)\, {\rm Tr}[\partial_\mu U^\dagger \partial^\mu U] - V(h)$$

- Geometrical form $\phi = (h, \pi^1, \pi^2, \pi^3)$

$$\mathcal{L}_{\rm HEFT} = \frac{1}{2} g_{ij}(\phi)\, \partial_\mu \phi^i \partial^\mu \phi^j - V(\phi)$$

Alonso, Jenkins, Manohar
1511.00724. 1605.03602

Adding spin-0

- Generalization with spin-0 particles:

$$\mathcal{L}_{\mathrm{HEFT}} = \frac{1}{2} g_{ij}(\phi)\, \partial_\mu \phi^i \partial^\mu \phi^j - V(\phi)$$

$$\phi = (h, \pi^1, \pi^2, \pi^3, S, H^+, H^-, \cdots)$$

- The "charged" scalar manifold can be constructed by Callen-Coleman-Wess-Zumino (CCWZ) method.

Nagai, Tanabashi, Tsumura. Uchida,
1904.07618 (PRD)

Talk plan

- Adding spin-0

  1904.07618 (PRD)

- Adding spin-1/2

  2102.08519

Fermionic extension

$$\mathcal{L}_{\mathrm{HEFT}} = \frac{1}{2} g_{ij}(\phi)\, \partial_\mu \phi^i \partial^\mu \phi^j - V(\phi)$$

- SUSY !

(Weyl) fermion

$$\phi^i \Rightarrow (\phi^i, \phi^{\dagger i^*}, \psi^i, \psi^{\dagger i^*})$$

$$g_{ij}(\phi) \Rightarrow g_{ij^*}(\phi, \phi^\dagger)$$ Kähler metric

$$V(\phi) \Rightarrow P(\phi) \;\; P^\dagger(\phi^\dagger)$$ Superpotential

SUSY HEFT

$$\mathcal{L}_{\text{scalar}} = g_{ij^*}(\partial_\mu \phi^i)(\partial^\mu \phi^{\dagger j^*}) - g^{ij^*} P_{,i} P^\dagger_{,j^*}$$

$$\begin{aligned}\mathcal{L}_{\text{fermion}} = & \frac{i}{2} g_{ij^*} \psi^{\dagger j^*} \bar{\sigma}^\mu \overset{\leftrightarrow}{\partial}_\mu \psi^i \\ & + \frac{i}{2}(g_{ij^*,k}\, \partial_\mu \phi^k - g_{ij^*,k^*}\, \partial_\mu \phi^{\dagger k^*})(\psi^{\dagger j^*} \bar{\sigma}^\mu \psi^i) \\ & - P_{;ij}(\psi^i \psi^j) + h.c. \\ & - \frac{1}{8} R_{ik^* jl^*}(\psi^i \psi^j)(\psi^{\dagger i^*} \psi^{\dagger j^*})\end{aligned}$$

Generalized HEFT

NEW!

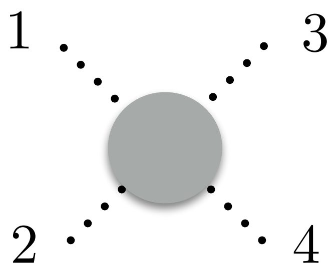
$$
\begin{aligned}
\mathcal{L}_{\text{scalar}} &= \frac{1}{2} g_{ij} (\partial_\mu \phi^i)(\partial^\mu \phi^j) - V(\phi) \\
\mathcal{L}_{\text{fermion}} &= \frac{i}{2}\, g_{\hat{i}\hat{j}^*}\, \psi^{\dagger \hat{j}^*} \bar{\sigma}^\mu \overleftrightarrow{\partial}_\mu \psi^{\hat{i}} \\
&\quad + \frac{i}{2} (g_{k\hat{j}^*,\hat{i}} - g_{k\hat{i},\hat{j}^*})(\psi^{\dagger j^*} \bar{\sigma}^\mu \psi^i)(\partial_\mu \phi^k) \\
&\quad - \frac{1}{2} M_{\hat{i}\hat{j}}\, (\psi^i \psi^j) + h.c. \\
&\quad - \frac{1}{4} R_{\hat{i}\hat{k}^*\hat{j}\hat{l}^*} (\psi^{\hat{i}} \psi^{\hat{j}})(\psi^{\dagger \hat{k}^*} \psi^{\dagger \hat{l}^*}) \\
&\quad - \frac{1}{12} R_{\hat{i}\hat{l}\hat{j}\hat{k}} (\psi^{\hat{i}} \psi^{\hat{j}})(\psi^{\hat{k}} \psi^{\hat{l}}) + h.c.
\end{aligned}
$$

- can be constructed by CCWZ method. **Nagai,** Tanabashi, Tsumura. Uchida, 2102.08519

On-shell amplitudes

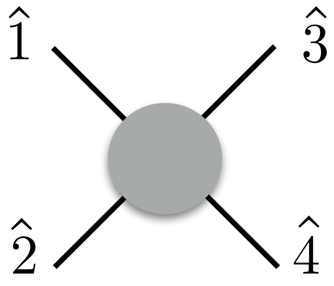
- High-energy on-shell amplitudes probe the “curvature”.

SSSS



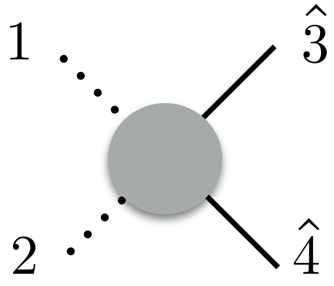
$$\sim R_{1234}\, s$$

FFFF



$$\sim R_{\hat{1}\hat{2}\hat{3}\hat{4}}\, s$$

SSFF



$$\sim R_{12\hat{3}\hat{4}}\, s$$

* See 2102.08519 for complete expressions.

Summary

- We have generalized HEFT by extending the field space.

$$
\begin{aligned}
\mathcal{L}_{\rm scalar} &= \frac{1}{2} g_{ij} (\partial_\mu \phi^i)(\partial^\mu \phi^j) - V(\phi) \\
\mathcal{L}_{\rm fermion} &= \frac{i}{2}\, g_{\hat{i}\hat{j}^*} \psi^{\dagger \hat{j}^*} \bar{\sigma}^\mu \overleftrightarrow{\partial}_\mu \psi^{\hat{i}} \\
&\quad + \frac{i}{2} (g_{k\hat{j}^*,\hat{i}} - g_{k\hat{i},\hat{j}^*})(\psi^{\dagger j^*} \bar{\sigma}^\mu \psi^i)(\partial_\mu \phi^k) \\
&\quad - \frac{1}{2} M_{\hat{i}\hat{j}} \, (\psi^i \psi^j) + h.c. \\
&\quad - \frac{1}{4} R_{\hat{i}\hat{k}^*\hat{j}\hat{l}^*} (\psi^{\hat{i}} \psi^{\hat{j}})(\psi^{\dagger \hat{k}^*} \psi^{\dagger \hat{l}^*}) \\
&\quad - \frac{1}{12} R_{\hat{i}\hat{l}\hat{j}\hat{k}} (\psi^{\hat{i}} \psi^{\hat{j}})(\psi^{\hat{k}} \psi^{\hat{l}}) + h.c.
\end{aligned}
$$

- On-shell amplitudes probes the "geometry".